NARROWBAND COHERENT DATA TRANSMISSION-MOBILE

Bateman, A. and McGeehan, J.P.

Communications Research Group, University of Bristol

INTRODUCTION

For almost all future mobile radio services, whether it be mobile satellite, aeronautical, cellular, or PMR communications, the reliable transmission of data will be of paramount importance. The desired goals of high data throughput with low error probability seem completely incompatible for a mobile radio link subject to multipath fading, carrier frequency errors, doppler shift, etc. The key to the problem lies in the effectivness of "channel equalisation" techniques and coding strategies tailored to the particular operating environment in question.

In the absence of multipath propagation and vehicle motion, eg. a fixed link radio communications system, the channel is almost ideal for data transmission, and with well engineered transciever equipment can accommodate significantly higher data rates than a conventional landline communications channel of equivalent bandwidth. Similar high performance can be realised with mobile communications links, (assuming adequate signal power), provided that rapid channel equalisation is incorporated to mitigate the multipath propagation effects. For narrowband communications links, (those which operate well within the coherence bandwidth), the channel can be modelled with a linear transfer function. This means that a single frequency component, eg. a pilot tone, can be used to determine the transfer characteristics of the entire channel and be used to generate an appropriate inverse transfer function for channel equalisation. This process is commonly referred to as pilot tone channel sounding. Many people argue that the use of a pilot sounder sent in addition to the data signal is wasteful of both power and bandwidth and advocate that the data signal itself should be used to determine the channel transfer function more economically. The problem with this approach, as is demonstrated in later sections, is that unless the data rate and modulation format are carefully selected, it is not possible to separate the channel transfer function information from the digital information and imperfect channel equalisation and data detection results.

The alternative approach for mobile communication, and that currently adopted by most service providers, is not to bother with channel equalisation and sounding at all, but rather to build sufficient redundancy into the data system, such that a low bit rate but reliable communications link can be guaranteed. It can only be said that this approach, in the light of a practical alternative, is hardly justifiable as a spectrally efficient communications technique.

The remainder of this paper is concerned with the practical realisation of pilot based channel equalisation systems, their integration into coherent data demodulation techniques and their performance compared with coherent data systems exploiting the data signal alone. Most of the analysis given is associated with the land mobile environment, which is arguably the most hostile environment for data transmission, however many of the results and remarks made are equally applicable to the aeronautical, sea and satellite mobile fields.

PILOT BASED COHERENT DATA SYSTEMS

If the pilot reference tone is acting solely as a channel sounder, ie. it does not play any part in the data detection process, then the positioning of the pilot relative to the data signal is of no consequence, provided of course that it lies within the allocated transmission bandwidth and within the channel coherence bandwidth. By monitoring the random amplitude and phase variations of the incoming pilot, which exactly mimic those imposed on the data bearing signal, suitable inverse gain and phase modulation can be applied to the data waveform thereby cancelling the multipath distortion. This process is illustrated in Fig 1. A well established technique for this purpose is known as Feedforward Signal Regeneration (FFSR) [1]. Having compensated for the channel imperfections, conventional techniques for coherent data demodulation can be applied, typically involving Nth power tracking loops for carrier regeneration.

Whilst a perfectly practical means of realising coherent mobile communications, the dual process of channel equalisation followed by carrier regeneration and subsequent data demodulation seems a somewhat inefficient technique. A far more elegant solution is to perform channel equalisation and data demodulation simultaneously thereby minimising circuit complexity and error. The most obvious means of accomplishing this task is to retain a diminished level data carrier to act as the pilot tone. Provided the received fading pilot can be extracted unambiguously from that data modulation, then a suitable "inverse fading" data carrier can be generated which, when multiplied with the incoming data signal, will perform the functions of fading compensation and data detection simultaneously. The difficulty with this approach lies in separating a diminished data carrier from the data modulation.

Single Pilot TCT

For the trivial case of Binary Phase Shift Keyed modulation, line coding techniques such as Manchester coding can be applied to the incoming data stream to ensure a low spectral energy about the data carrier, Fig 2. Such a technique has been recently investigated by JPL and the GE company for mobile satellite data communications, called the Tone Calibration Technique, (TCT) [2]. The attraction of the technique is the simplicity of the processing involved and the potential to provide reliable coherent data demodulation in a multipath environment. The fundamental constraint of the system however lies in the need for line coding of the data. The degree of line coding is dictated by the frequency uncertainty in the received data carrier, primarily due to Doppler effects. Operation of the TCT system in the proposed mobile satellite bands is severely hampered by this constraint, particularly when attempting to exploit the more spectrally efficient M-ary modulation techniques as one would like.

Dual Pilot TCT

A second system proposed by JPL, which overcomes many of the limitation in the single pilot TCT system, is a dual pilot reference technique [3], Fig 3. Here, rather than using a single diminished level data carrier, two pilot tones are employed, placed strategically at the edges of the shaped data spectrum. By extracting and mixing together the two pilot tones, a component at twice the data carrier frequency is generated, which, after frequency division by two is avaiable for channel compensation and data detection. Whilst overcoming the line coding constraint of the original TCT system, there are unfortunately three main drawbacks with the dual pilot technique. Firstly, greater bandwidth is required to accommodate the additional pilot tone. Secondly, the pilots are located at extremes of the channel band where amplitude and phase characteristics are least stable and the pilots are most susceptible to adjacent channel interference. Thirdly, the carrier generation process involves frequency division by two. This latter factor not only introduces 180^{o} of phase ambiguity which implies differential data encoding and a corresponding penalty in error performance, but also results in a high irreducible error rate when operating in a rapid fading environment.

The reason for the irreducible error rate is two fold. Firstly, the conventional D-type frequency dividers do not perform continuous phase division and hence the recovered data carrier is not truly phase coherent. Secondly, in exactly the same way that squaring of a binary phase shift keyed carrier eliminates the phase transitions and hence the data modulation for carrier regeneration purposes, so mixing of the two pilot tones in the TCT system unfortunatly eliminates vital information about the random phase reversals that occur at the bottom of deep fades [4]. The result is that the recovered data carrier undergoes a periodic false phase reversal relative to the incoming data signal, Fig 5 and thus loses coherency. By virtue of the differential encoding the ambiguity only results in a single bit error for each false phase state. However with Rayleigh fading, this phenomena occurs frequently giving rise to the irreducible error rate characteristic.
One advantage of the dual pilot tone system arises from the fact that the spacing between the two pilots remains constant regardless of any random phase/ frequency error on the channel. If the pilots separation is chosen to be some convenient multiple of the data clocking frequency, then by measuring the difference frequency between the received pilot tones, a simple clock recovery system is implemented.

Transparent Tone In Band (TTIB)

A contender and forerunner to the single and dual pilot TCT data techniques is a system known as Transparent Tone in Band (TTIB) [5]. This system was first proposed in 1979 as a means of obtaining coherent data detection for M-ary data formats in the multipath environment, as well as a reference configuration for SSB voice communications. The technique employs a central reference tone which can be the diminished level data carrier, and removes energy from the tone position, not by line coding techniques, but by physically parting the input signal spectrum at or near the tone frequency to create a suitable spectral notch, Fig 4. This approach means that firstly, no information is lost from the input signal, and secondly, that a variable "notch width" can be provided simply by controlling the extent to which the two halves of the data spectrum are separated.

On reception, the pilot reference is filtered out and the two remaining spectral portions recombined. Data detection is then acomplished in an identical manner to that used by the single tone TCT system. Because no energy has had to be removed from the transmitted data signal, and recourse to line coding techniques is unnecessary, the performance of the TTIB system is markedly superior to the TCT approach. Further, as the process is independant of the type of modulation used, it can be readily adapted for use with M-ary signalling systems, providing one of the simplest means of coherent detection for fixed and mobile data modems alike.

The TTIB system also conveys clocking information in a similar manner to that of the dual pilot TCT system. Instead of using two pilot tones however, the TTIB clocking reference is conveyed by the degree of band separation between the two halves of the data spectrum [6].

Data derived reference systems

When proclaiming the virtues of a pilot-based data communications system, one is always faced with the question; Why waste power in the pilot when all the information required for channel compensation is conveyed in the data signal itself?

Consider the simple case of Binary Phase Shift Keying with a squaring or Costas tracking loop providing the carrier synchronisation. There are three major problems associated with this type of system when operating in the fading environment. The first problem is that shaping of the transmitted data spectrum to achieve high spectral efficiency reduces the power and purity of the regenerated carrier. Secondly, the bandwidth of the carrier tracking loops needs to be considerably greater than the frequency uncertainty of the data signal due to the wideband nature of the multipath induced phase modulation [7]. The result is that the noise rejection properties of the loop and hence the phase coherence of the recovered carrier are prohibitively degraded. The third factor is the problem of false phase reversals of the carrier during deep fading as explained in the previous section. This factor alone results in an irreducible error rate floor for the modem.

From the above analysis of the somewhat trivial case of BPSK, it should be immediately apparent that the performance of more sophisticated systems requiring higher orders of carrier recovery tracking loops is likely to be totaly unacceptable and is in fact often far worse than that of the cheaper, less sophisticated non-coherent data techniques such as FSK.

BIT ERROR RATE PERFORMANCE FOR PILOT-BASED DATA COMMUNICATIONS

There can be little doubt that pilot based coherent data modems are an attractive and practical means of achieving coherency in the mobile environnment, but at what cost in performance with the additional power and bandwidth required for pilot insertion. A number of recent articles have analysed this exact problem [8,9,10] and have largely reached the same conclusion, namely *that the performance of a* pilot-based coherent data system is only 1 to 2 dBs worse than the theoretical optimum. The authors have shown [10], that the bit error probability for a TTIB based CPSK system is given by that of an equivalent Differential PSK modem, without, however, exhibiting the very high irreducible error rate phenomena associated with actual DPSK modems operated in the fading environment. The performance of the pilot system compared with a conventional carrier recovery CPSK modem using for example the squaring loop, is shown to be vastly superior under fading conditions, and at least as good under static or white noise conditions. In other words, the pilot based modems, despite the additional power and bandwidth required, can outperform all other types of modem in a mobile fading environment, without sacrificing performance in a non-fading environment. These results are demonstrated in Fig 6, which shows the bit error probabilities for the various systems under fading and static operating conditions. The arguments and analysis presented for the BPSK case can readily be extended to M-ary systems with the same result.

CONCLUSIONS

The paper has set out to provide a theoretical comparison of techniques for realising coherent data communications in the hostile mobile environment. Much of the analysis has been centred on pilot-based techniques, whereby a pilot tone is sent in addition to the data modulation to enable channel sounding and subsequent multipath cancellation. Ideally the pilot also performs the task of data detection simultaneously. Of the growing number of pilot techniques proposed in recent years, it is argued that the Transparent Tone-in-band (TTIB) technique is the most flexible and optimum, being capable of accepting almost all modulation formats and achieving not only coherent data detection but providing accurate clock timing without recourse to the conventional, often complex, clock and carrier recovery systems.

It is found that performance loss incurred by the additional power and bandwidth requirements of the pilot tone, typically less than 5% of the total system requirement, is in the order of 1 to 2dBs when compared with the theoretical optimum. By comparison with the performance of practical coherent modems using conventional data aided carrier recovery techniques, the pilot tone system is found to be markedly superior. In a "non-fading" additive white Guassian noise environment, both techniques exhibit similar bit error probability statistics. However, under Rayleigh fading conditions, where high irreducible error rate characteristics hamper the application of conventional modem designs, the pilot reference techniques are found to operate totally satisfactorily with the irreducible error phenomena eliminated.

The potential of a pilot based data system such as TTIB, is best utilized, not with simple binary coherent communications, but with the more complex yet bandwidth and power efficient modulation techniques such as 16QAM or 16PSK. Whilst being virtually impossible to realise with conventional technology, considerable success is being experienced with the use of these formats when operated with the TTIB system.

References

1. McGeehan J.P and Bateman A. "Theoretical and Experimental Investigation of Feedforward Signal Regeneration as a Means of Combatting Multipath Propagation Effects in Pilot-Based SSB Mobile Radio Systems", IEEE Trans. VT-32, 1983, pp106-120.

2. Goode S.H. "An Evaluation of the Tone Calibration Technique for Data Transmission Over Land Mobile Radio Channels". IEEE VT Conf. May 1985, pp140-145.

3. Simon M.K. "Dual Pilot Tone Calibration Technique". IEEE Trans. VT-35. pp63-70.

4. Bateman A. "Advanced Signal Processing Techniques for SSB Mobile Radio", PhD Thesis, 1983.

5. Bateman A. and McGeehan J.P. "Phase locked Transparent Tone-in-Band (TTIB): A New Spectrum Configuration Particularly Suited to the Transmission of Data Over SSB Mobile Radio Networks", IEEE Trans. COM-32, 1984, pp81-87.

6. McGeehan J.P and Bateman A. "Simple Carrier and Bit Synchronisation System for Narrowband Data Transmission" IEE Proc. Pt F. Vol 132, 1985, pp69-72.

7. Sladen J.P.H and McGeehan J.P "The Performance of Combined Feedforward AGC and Phase Locked AFC in a Single Sideband Mobile Radio Receiver." IEE Proc. Pt F. Vol 131, 1984, pp437-441.

8. Rafferty W, Anderson J.B, Saulnier G.J and Holm J.R. " Laboratory Measurements and a Theoretical Analysis of the TCT Fading Channel Radio System", IEEE Trans. Com-35, 1987, pp172-180.

9. McGeehan J.P and Bateman A. "Data Transmission over UHF Fading Mobile Radio Channels", IEE Proc. Pt F. Vol 131, 1984, pp364-374.

10. Bateman A. and McGeehan J.P, "Coherent Demodulation of Pilot Tone Single Sideband with Phaselocked TTIB/FFSR Processing.", IEE Proc. Pt F. Vol 132, 1985, pp363-365.

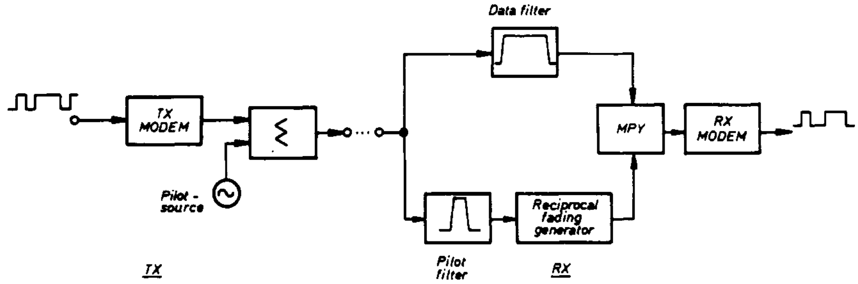

FIG.1 GENERALISED PILOT-BASED MOBILE DATA SYSTEM

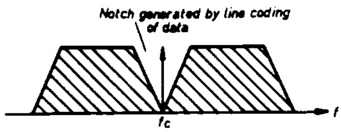

FIG.2 SINGLE PILOT TCT SPECTRUM
CONFIGURATION

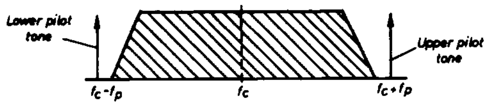

FIG.3 DUAL PILOT TCT SPECTRUM
CONFIGURATION

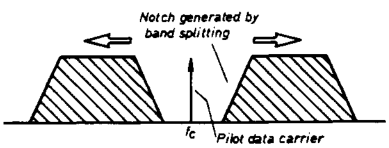

FIG.4 TRANSPARENT TONE-IN-BAND (TTIB)
CONFIGURATION

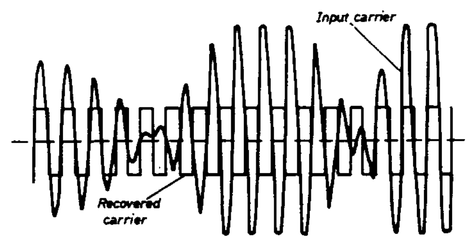

FIG.5 RECOVERED DATA CARRIER FROM SQUARING CARRIER
REGENERATION SYSTEM SHOWING FALSE PHASE
REVERSALS DURING FADING

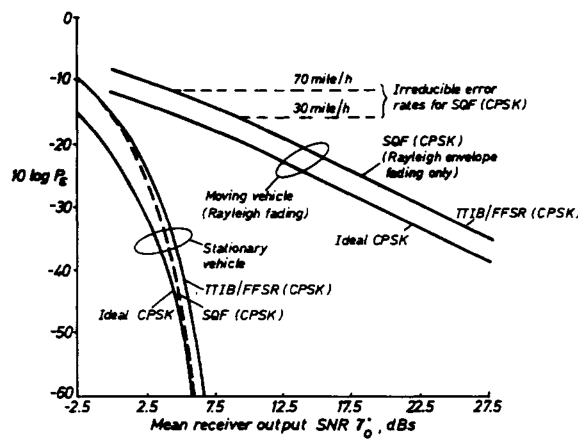

FIG.6 BIT ERROR PROBABILITY FOR A PILOT-BASED BPSK
DATA SYSTEM AND A CONVENTIONAL CARRIER
REGENERATION COHERENT DATA SYSTEM